[redacted]



R. Wojdyla
Robert E. Vauet

Technical Report No. 30 I

( PART 1 - TEXT )

SACLANT ASW
RESEARCH CENTRE

# SHORT-PERIOD VERTICAL DISPLACEMENTS OF THE UPPER LAYERS IN THE STRAIT OF GIBRALTAR

by

R. FRASSETTO

1 November 1964

[redacted]

VIALE SAN BARTOLOMEO, 92
LA SPEZIA, ITALY

[redacted]

AD 0808764

TECHNICAL REPORT 30

SACLANT ASW RESEARCH CENTRE
Viale San Bartolomeo 92
La Spezia, Italy

# SHORT-PERIOD VERTICAL DISPLACEMENTS OF THE UPPER LAYERS IN THE STRAIT OF GIBRALTAR

By

R. Frassetto

APPROVED FOR DISTRIBUTION

HENRIK NØDTVEDT
Director

TABLE OF CONTENTS



FIGURES: All Figures are in the separate Part 2.

# SHORT-PERIOD VERTICAL DISPLACEMENTS OF THE UPPER LAYERS IN THE STRAIT OF GIBRALTAR

By

R. Frassetto

## ABSTRACT

Short-term vertical displacements of the upper water layers in the Strait of Gibraltar are illustrated and discussed.

As a background to this subject, a brief description of the hydrology and the long-term vertical displacements of the surface layers is first presented. This is based on observations made by various authors prior to 1957 and by three expeditions organised by the NATO Sub-Committee on Oceanography in the summer periods of 1958, 1960, and 1961.

The principal part of the report is based on observations of short-term displacements made by the author in the summer periods of 1958, 1959, and 1961, using primarily the Woods Hole Oceanographic Institution's thermistor chain.

These thermistor chain records revealed independent trains of internal waves superimposed on each of the semidiurnal waves of the tidal period. It was found that these waves had amplitudes varying from 40 m to 120 m, wave lengths from 200 m to 1500 m, and periods from 10 to 40 minutes. The length of each train averaged 4 1/2 miles from leading to trailing wave, each wave being slightly lower than the one before. The waves generally formed over the submarine sill that lies west of Tarifa and moved eastwards into the Mediterranean at speeds that increased up to a value of 5 knots by the time they had travelled

16 miles. They were found to have vanished completely within a distance of 50 miles (i.e., 30 miles east of the Rock).

The leading waves of these trains involved most of the upper layer of water, the lower interface of which slopes irregularly upwards from the Sill eastwards and from south to north across the Strait. The Deep Scattering Layers, which became involved in this movement, were found to oscillate sinusoidally at depths of 230 m to 250 m. Above the crests of these leading waves, long bands of ripples were seen to form at the surface and, in favourable wind conditions, to form breakers visible on a radar screen. From the air, these parallel bands of ripples were observed to extend up to 6 miles at approximately right angles to the axis of the Strait. The front of each wave train was found to be characterised by an upwelling of the intermediate water layer, which thereby cooled the surface temperature along this line by an average of $4^{\circ}C$.

By using pitot tubes installed on the thermistor chain, simultaneous current measurements were obtained. These indicated particle velocities which suggest that the short-term vertical displacements may be interpreted as internal waves.

## 1. INTRODUCTION

The complex morphology of the Strait of Gibraltar is shown in Fig.1[1], which is a photograph of a relief model constructed (by the Istituto Geografico Militare of Florence) on the basis of bathymetric data supplied by this laboratory. The model clearly shows that both the coastline and the sea bed are rougher and more irregular to the west.

Recent geological investigations (Ref. 1) favour the theory that the Strait represents a Graben system with two faults east and west of the Sill. The Sill itself is the submerged link of the stable arch structure of the Bétic Cordillera (Spain) and the Rif Mountains (Morocco), eroded by submarine currents. It forms an irregular submarine barrier about 6 miles wide below the level of the Continental Shelf and is actually composed of two sill depths of about 300 m north and south of a central rise 150 m deep.

On the Atlantic side of the Sill, the fault is divided into two channels by the submarine Spartel Ridge and has a meandering shape and a rough character with deep holes. This shape is probably also a product of erosion by dense Mediterranean water flowing westward, mostly in the southern channel where the minimum depth is an almost constant 400 m. In this channel, the Mediterranean water begins a deep, gradual mixing process with the overlying Atlantic water.

On the Mediterranean side of the Sill, the fault has formed a more uniform and deeper channel with an average depth of 800 m. It is believed that horizontal stresses contributed to the formation of this deep channel, pushing the Sill barrier at least 10 miles to the west. The slopes of this channel are steep, and even conventional echo-sounders give values of $16^{\circ}$ to $30^{\circ}$. At the edge of the

[1] All figures appear in the separate Part 2.

Shelf, these slopes are striated by small canyons and gullies of a purely local nature. A detailed study of the bottom with narrow-beam transducers and electronic navigation may reveal the details of these features and possibly, in the vicinity of the Rock, submarine cliffs. This eastern channel is not eroded by deep currents. Here unmixed, dense Mediterranean water flows slowly westwards below a layer of lighter, incoming Atlantic water which thereby undergoes a mixing process near the interface.

The pattern of this exchange of waters between the Mediterranean and the Atlantic is shown in Fig. 2, which portrays the salinity profiles in summer and the circulation of the water masses longitudinally through the Mediterranean and out into the Atlantic. The vertical cross-section is from the Levantine coast at A, through the Strait of Sicily at B, the Strait of Gibraltar at C, to a point D in the Atlantic. Using the "core" method of analysis, as developed by G. Wüst, one can follow the path of Levantine water from its source region between Cyprus and Rhodes as it branches out westwards. One of these branches (broken line on Fig. 2), which follows the African coastline, spills out into the Atlantic over the Sill (C) of the Strait of Gibraltar, where it then sinks to about 1000 m and gradually loses its original characteristics.

Similarly, one can follow the core of the Atlantic water (dotted line) entering through the Strait to replace the lost Mediterranean water. This branches off in the Mediterranean, eventually reaching the eastern end and completing the circulation pattern. (Refs. 2 and 3).

It was seen that the tongue of higher salinity Mediterranean water spilling out through the Strait of Gibraltar finds its level between about 500 m and 1500 m. Figure 3 shows how, at this depth, it turns northwards along the coast of the Iberian Peninsula under the influence of the Coriolis force, gradually diffusing into the Atlantic water. Its horizontal extent into the waters between Portugal and the Azores at the core depth of 1000 m is shown in Fig. 4 (Ref. 2).

The balance of the water economy in the Mediterranean is the basic factor determining the two-way flow through the Strait of Gibraltar, and therefore any long-term variation in this budget will have a repercussion on the quantity of water flowing in and out through the Strait (Refs. 2, 4). The interaction of the two hydraulic heads of the dense Mediterranean water and the higher Atlantic water produces an effect comparable in some ways to a meteoroligical warm front, in which the lighter medium over-rides the heavier at an angle. In this case, however, the movements of the two media are in completely opposite directions and the east-going Atlantic water is over-riding west-going Mediterranean water. In addition to this slope of the interface along the axis of the Strait, the influence of geostrophic forces creates another slope upwards from south to north across the axis.

The depth of the interface changes with the seasons, with the tidal changes from neaps to springs, with the piling-up effect of the prevalent westerly or easterly winds, and with the atmospheric pressure differential between areas west and east of the Strait. In addition, the interface is subject to the vertical displacement of the semidiurnal tidal period and to rapid and wave-like displacements of shorter period. The interface is further disturbed by vertical and horizontal eddies formed where the sea bed is particularly rough, where the striated submarine slopes are most irregular (west of the meridian through Tarifa), over shallows, or over the Sill. Time-series of temperature and salinity measurements have shown occasional sharp steepening of the profile, suggesting dynamic instabilities that may give rise to internal breakers and great turbulence (Refs. 2, 5). A bore-like stream over 50 m thick has been found to run from the Sill towards the eastern end of the channel just after High Water; this produces a sharp increase of speed which may be as much as 4 knots in a few minutes at a given spot.

## 2. AREAS OF RESEARCH

Oceanographic studies of the Strait of Gibraltar started in 1921 but, apart from the temperature and salinity measurements of entire semidiurnal tidal periods obtained in 1921 and 1928 by the Danish research vessel DANA, the early studies do little to explain the complicated dynamics of the Strait and are not considered here.

Figure 5 shows the areas in which the studies of temperature, salinity, and currents used as a basis for this present work were made. Apart from the DANA measurements already mentioned (shown on the map by the two circles marked 1921 and 1928), they consist entirely of the work of Lacombe and his group in conjunction with the NATO Sub-Committee on Oceanography in 1958, 1960, and 1961, and of the author in cooperation with the Woods Hole Oceanographic Institution (WHOI) in 1958, 1959, and 1961

The circles marked on Fig. 5 represent the stations held - sometimes for several days and sometimes by several ships simultaneously - by the different ships that made studies at fixed points. The broken lines show the tracks - or, in the cases of 1961, enclose the area of a large number of tracks - followed by ships making measurements while underway.

As the area east of the Sill has the advantage that within it the lower Mediterranean water is almost completely homogeneous, either the $13^{\circ}C$ isotherm or the 38‰ isohaline* can be used here to outline the lower interface of the disturbed surface layers. For this reason the author has so far concentrated all his work (with the exception of a few verification studies to the west) in this area, using

---

*The actual salinity of this water is slightly higher - probably about 38.2‰ - but until this is determined definitely it is thought better to use the round figure approximation of 38‰.

the more easily obtainable isotherm data as a representative parameter. When a better understanding of the processes has been obtained in this simpler area, it is hoped to extend similar studies to the area over and west of the Sill.

The series of measurements made by the author is summarised as follows:

In August 1958 the U.S.S. YAMACROW towed the newly-developed, 200 m long, WHOI thermistor chain on 70 runs of 6 miles long across the Strait just east of the Sill and on one run along the axis of the Strait (see dotted lines in Fig. 5). The transverse runs were made at a speed of 6 knots, the longitudinal run at a speed of 11 knots (Ref. 6). In July 1959 (see dash-dotted lines in Fig. 5), towing the thermistor chain from the CHAIN, continuous recordings of the isotherms as functions of both depth and time were made for periods of up to 3 days from the stations marked N, S, and E on Fig. 5. In addition, runs were made around the Sill (the square pattern around N and S on Fig. 5) on two longitudinal tracks, and on a line from off Great Europa Point to off Almina Point, to obtain time-space series of temperatures and the Deep Scattering Layer during single diurnal periods. Finally, a train of internal waves - which was the particular object of the 1959 study - was followed from position E towards the Mediterranean as far as its vanishing point. In September 1961 the CHAIN (see area enclosed by broken line in Fig. 5), towing its thermistor chain, was again used and made 27 longitudinal runs designed to define the limits within which short-term internal waves occur and to study their characteristics. On this occasion pitot tubes were added to the thermistor chain to measure current shear.

Interpretation of the measurements from all the studies shown in Fig. 5 must take into account the fact that the data were collected at intervals and with non-continuous systems. The new equipment to be used in future studies will permit long-term recordings and provide for better understanding of conditions in the Strait.

## 3. REGIONAL DIVISION OF THE STRAIT

A simplified model of the hydrology of the Strait is shown in Fig. 6, in which the upper diagram represent the salinity and current distributions along the vertical plane through the axis of the Strait, and the lower diagram represents the current distribution along the horizontal plane of the sea surface.

In the vertical section the 38‰ isohaline, which has been found to be at about the same depth as the $13^{o}C$ isotherm, has been chosen to represent the interface between the lower Mediterranean water and the upper water of the Atlantic characteristics. The heavy line shows the average depth of this isohaline, and the broken lines on either side show the range of depths observed in different years, in different conditions, and at different seasons and tidal periods.

At a glance, one can see that the Strait can be divided into the five main regions of differing dynamic characteristics described below and delineated by the transverse lines on the lower diagram and by the vertical lines on the upper diagram.

The Ridge Region. In the western entrance the predominantly Atlantic water, outlined by the 36‰ isohaline, acts as a hydraulic head pressing against the Mediterranean water (below the 38‰ isohaline). This pressure varies with the tidal period and periodically pushes the Mediterranean water over the Sill, so that the interface often assumes sharp slopes and can, in extreme conditions, approach the vertical. At the surface the region is characterised by currents flowing eastwards along the constricting coastlines; when these assume high velocities, large eddies are produced near the axis of the Strait, and a reversal of current towards the west may occur, as shown in the lower diagram.

The Sill Region. This is characterised by the maximum amplitude of interface oscillations, by upwelling currents and by large surface eddies, all of which

vary as a function of time according to prevailing conditions.

The Tarifa Region: Characterised by a sharper slope of the interface, a diminishing amplitude of oscillations, and upwelling currents. The last generate current reversals and return of the west-flowing Mediterranean water towards the east. The turbulence thereby produced emphasises the mixing process at the interface. In this region the scarcity of sound scattering features, which are dense in the other regions, may indicate strong vertical eddies (Ref. 6).

The Gibraltar Region: This appears to have comparatively simple characteristics. The bottom layer of nearly homogeneous Mediterranean water is 600 m to 700 m thick and the range of oscillations at the interface is reduced to approximately 80 m - 120 m.

The Eastern Entrance: Here the disturbed surface water fans out into the Mediterranean, energy is dissipated rapidly, and the two layers resume a more normal condition.

In Fig. 6, the average profile of the interface is shown only in a section along the axis of the Strait. A profile in the other direction, normal to the axis, would show that the depth of the interface decreases towards the north and increases towards the south. The slope of the interface is irregular, often in steps, and changes its angle with the changes of the tide. These characteristics are principally the result of the Coriolis force and will be observed later in the transverse temperature profile in Fig. 8.

## 4. REGIONAL CURRENT CHARACTERISTICS

The differing characteristics of current behaviour in the various regions of the Strait may be seen from the examples given in Fig. 7. These show the speed of the current at various depths, expressed as a function of the tidal

period. Each graph shows measurements made throughout a 12 hr tidal period at a certain point along the axis of the Strait, and each individual trace shows the measurements made at a specific depth, measured in metres, as indicated by the arrowed numbers. (Ref. 7).

In general the currents at all recorded depths are in phase throughout the Ridge Region (represented by $A_4$), the Sill Region, and the Tarifa Region (represented by $B_2$). On all three of these graphs it is seen that there is a westward movement a few hours before high-water at Gibraltar and an eastward movement a few hours after high-water. The strength of this movement varies at different depths, but in these three regions it is in phase at all depths.

Further east, however, in the Gibraltar region (represented by $C_2$) the currents at different depths were found to have different phases and, moreover, the previous eastward-westward changes almost completely disappear.

Strong velocities (up to 4 knots) are found in the Sill Region, where the whole mass of water from surface to bottom is seen to move eastward and westward in phase. In the Tarifa Region current reversals are found below 200 m, while the surface layer flows eastwards without reversal (see changes at 10 m and 50 m). One of the most interesting features in this region is that the change of current speed occurring 1 1/2 hr after high-water is extremely rapid (in the example shown there is an almost instantaneous increase of speed of 2.8 knots at 10 m and of 3.5 knots at 50 m) and takes the form of a bore. It is hoped to investigate this phenomenon more closely during future studies.

Although the data shown in Fig. 7 are considered to be generally representative of the different regions in the particular tidal conditions, it has to be remembered that they are only single sets of measurements through one tidal period and at one specific point. The measurements at the Sill, for instance, were made over its southern side; it could be expected that

contemporaneous measurements over the northern side would be quite different in detail, although probably not in general character.

## 5. TEMPERATURE CHANGES AT THE SILL

The upper diagram in Fig. 8 shows one of the time-space sequences recorded by the author during 35 double traverses over the Sill in August 1958. The ship, running at 6 knots on a 6 mile traverse, sailed from the southern end of the track (left side of trace) to the northern end (centre of trace) and back to the southern end (right side of trace). The diagram has been extracted from an earlier report on the subject in which the results are discussed in detail (Ref. 8).

It is sufficient here to observe the north-south slope and irregularities of the $13^{o}C$, $14^{o}C$, $15^{o}C$, and $16^{o}C$ isotherms and the fact that nearer the surface the isotherms scarcely participate in this effect. At other phases of the tide, however, it was found that the same isotherms had pratically no slope with the horizontal.

The continuously-recording thermometer mounted on the ship's hull often recorded surface temperature gradients of as much as $4^{o}C$ between north and south. Evidence of these is shown in the diagram, where the isotherms are seen to be well layered on the northern side of the Strait but seem to vanish to the surface on the southern side. Thus, on the northern side the surface water was warmer and the thermocline was sharper and shallower.

The records, of which this is a part, favour the theory of an intermediate layer between the surface layer and the bottom layer. Each of these layers can be expected to be characterised by its own flow speed and phase, as well as its depth and thickness, especially near the Sill. They may eventually also explain certain GEK surface current measurements made by Peluchon in 1961 (Ref. 9) which are not well understood and the results of which should be

taken with caution.

The lower diagram in Fig. 8 (Ref. 8) shows the oscillation of the internal tide at the Sill. The curves marked E to L represent the depth of the 13$^{o}$C isotherm at six fictitious stations (E to L) about 0.4 miles apart along the length of the run, (see upper figure). The rise and fall of this tide at the Sill is seen to be completely in phase with the local rising and setting of the moon; high tide occurs at 1200 and 2400 local lunar time.

In addition to this regular oscillation, it is also seen that the height of the internal high tide increases as the period of spring tides approaches, and that this is true on both northern and southern sides of the Sill.

The lower diagram is typical of conditions in the Sill Region, but it appears that further east, in the Gibraltar Region, the amplitudes are reduced and the time of the high internal tide is later.

## 6. IRREGULARITIES OF THE INTERFACE

Further evidence of the slopes and irregularities of the interface in the Sill Region and the Gibraltar Region is given by the isotherm profiles in Figs. 9 and 10. Both of these profiles were recorded by the thermistor chain in July 1959 immediately after spring tide.

Figure 9 is the most dramatic of four profiles made along approximately rectangular courses (the strong currents and surface eddies prevent accurate geometry in this area) over the Sill during a 9 hr period. Each run started from a point immediately over the Sill east of A and progressed in a clockwise direction through A, B, C, and D back to the start; the time taken for each run was only about 1 1/2 hr. The particular run illustrated was made between 2200 and 2330 local lunar time, which, as seen in Fig. 8, is just before high

internal tide at the Sill.

On this run, the $14^{o}C$ isotherm profile in the western half of the area is quite different from that in the eastern half. On the western side of the Sill (track BA), the isotherm is seen to be at about 100 m and of irregular character. On the eastern side (track CD) it is much smoother and much higher, sloping from 10 m in the north (near C) to 50 m in the south (near D).

The sudden change in depth of the isotherm north of the Sill (run BC) is very pronounced. On the other hand, south of the Sill (track AD) about 3/4 hr earlier, the isotherm was too low to be recorded by the thermistor chain. These phenomena can perhaps be explained by attributing them to the effects of the hydraulic head of Atlantic water pressing against the Mediterranean water mass. This hydraulic front could generate the vertical turbulence observed along track BA and the upwelling breaking mass along track BC. Further investigations of these processes are required.

In Fig. 10, which shows the isotherm profiles in the Gibraltar Region on the previous day, the pattern is much less dramatic. The figure shows two charts - one for the $14^{o}C$ isotherm and the other for the $15^{o}C$ isotherm - on each of which are drawn the profiles at both high and low internal tide (H. W. Gib. + 1 to 2 hr and H. W. Gib. - 5 to 6 hr respectively) taken across the axis of the Strait from Ceuta to Gibraltar. The effects of the tidal period are thereby clearly shown.

The most noticeable feature is the difference between the northern and southern sides of the axis. The variation in depth between the high and low internal tide levels of the isotherms is much less on the northern than on the southern side. The sharp slope of the isotherms near the axis during low internal tide is the principle characteristic outlining this feature.

The figure also reveals interesting temperature inversions on the southern side of the Strait. This is the type of feature that may be studied in greater detail on the long term recordings to be made in a forthcoming cruise.

## 7. SOUND-SCATTERING FEATURES

A study of sound-scattering layers in the Strait of Gibraltar has formed the subject of an earlier paper by the author (Ref. 6) in which some examples of PGR records collected in 1959 were given. Figure 11 now presents the complete set of records made at that time, during runs backwards and forwards from off Europa Point to off Almina Point (J-K on Fig. 10), because they appear relevant to this discussion.

It can be seen on the figure that at all times during the runs a dense deep-scattering layer is found near Europa Point (the point marked $N^{th}$ in the centre of each strip). This feature, often divided into several layers, is as thick as 40-50 fathoms (70-90 metres) during the night, when it is near the surface.

On the other side of the Strait, off Almina Point (marked $S^{th}$ at both ends of each strip) the scattering features are spread in several layers down to depths of 150 fathoms (270 metres). The distribution of the layers between the northern and southern side of the Strait varies at night according to the tidal phase. In runs 3 and 4, made during a rising tide, a distinct slope is observable in the lowest scattering layer. Near the centre of the Strait, where the layer is at about 100 fathoms, there are breaks in the layer that correspond to the shape of the isotherm profiles shown in Fig. 10.

At low tide (Run 2, L. W. Gib.) and high tide (Run 5, H. W. Gib.) the layer distributions are noticeably different. Although one could assume that these effects are caused by the dynamics of the Strait, their significance is not yet established.

## 8. SHORT-TERM OSCILLATIONS

Conditions of dynamic instability were shown in Fig. 8 by the profiles of the 14°C isotherm over the Sill. They can also be shown by the profiles of the isohalines during a single tidal period. Such a record, obtained by 1/2 hourly to hourly hydrographic casts from the DANA at its 1928 station (5 miles N.W. of Almina Point - see Fig. 4), is shown in Fig. 12.

On this record the internal tidal wave shows a sharp slope at H.W. + 3 1/2 hr, suggesting possible internal breakers or high frequency modes of oscillation. It was this record that first aroused the author's interest in recording variables in the Strait by means of continuous recording instruments. It was considered that short-term, high-amplitude oscillations, which are impossible to record by the conventional methods of sampling at hourly or longer intervals, could have been superimposed on the low frequency (semidiurnal) oscillations during certain phases of the tide.

The first evidence of these short-term oscillations was obtained by towing the thermistor chain at 11 knots along the axis of the Strait from west to east (Fig. 13). The record showed a 10 mile long train of 13 waves, the most noticeable feature of which was that, whereas the leading wave had an amplitude of 45 m, succeeding waves decreased in amplitude until the trailing wave had an amplitude of only 15 m.

If one accepts the theory that a train of waves is a disturbance generated at the Sill at a certain tidal phase, and progressing eastwards at a speed determined by the amount of energy involved, one would expect to record the arrival of the wave front at a given point at different times after high water. During a later survey on 20-21 July 1959, when the CHAIN held position against a low-drag marker buoy at Station E (Fig. 14), it was observed that the three wave fronts recorded arrived 5.05, 3.30 and 5.08 hours after the times of high-water in

Gibraltar which, according to the tide tables, occurred at 1413, 0228 and 1455 GMT. High water times show little daily difference, therefore one could scarcely attribute the difference on the wave front arrivals to daily difference of tides. On the other hand these three observations provide insufficient evidence from which to draw conclusions, for which a complete statistical study is required.

Figure 14 shows a neat train of twelve waves, the first three of which are outlined by three isotherms (14-15-16$^{\circ}$C) and reach a maximum amplitude of 75 metres near the second crest and a minimum of 13 metres at the trailing wave. The time interval from front to tail was about 3 1/2 hours. The train of waves progressed eastwards; how its speed differed from the current speed is not known, as, unfortunately, at that time current measurements could not be made.

## 9. VISUAL EVIDENCE AT THE SURFACE

As the trains of internal waves progress eastwards they fan out on leaving the Strait and entering the Mediterranean, thereby losing their energy and eventually vanishing completely at a distance of from 5 to 20 miles east of the Rock. On 20 July 1959, a wave front was followed by the ship from Position E until the point - 13 miles east - where its oscillations were no longer discernible on the thermistor chain record.

When following the front of a wave train by watching the instrumental records, it is often possible also to observe its position by visual observation of the surface. The first two or three waves of the train, which, it will be remembered, have the greatest amplitude, often generate long bands of ripples at the surface, each band being separated from the succeeding one by a stretch of smooth water. Such surface ripples - and slicks - are a known feature of internal waves in other parts of the world (Ref. 10). By taking

successive aerial photographs at the time when internal waves were recorded by the thermistor chain in the 1959 survey, it was found that these ripple bands extend from 3 to 8 miles across the Strait, progressing eastwards with the front of the wave train.

In certain conditions, these ripples break into lines of breakers, often high enough to be visible on the radar screen. Figure 15 shows a photograph of the radar screen on such an occasion, when the wind, blowing at 25 knots, was causing breakers to appear. At the time, the ship was drifting freely 6 miles south of the Rock, and the lines of breakers were moving eastwards past the ship in a direction $20^{\circ}$ to the north-east of the axis of the Strait and at about $45^{\circ}$ to the direction towards which the wind was blowing. On the photograph, two discrete lines of clutter represent breakers about 2 1/2 miles apart, but it was seen from visual observation that another line lay between these, probably too close to the ship to appear on the radar. The indications were that the wave length of the leading internal waves at this time was about 1 1/4 miles and that they extended at least 5 miles across the axis of the Strait.

## 10. OSCILLATIONS AT DEPTH

During all three expeditions on which this study is based, echoes from the deep scattering layers (DSL) were continuously recorded on a PGR. On these records it was possible to observe wave-like oscillations of the layers occurring at depths of 120-140 fathoms (215-250 m) - twice the depth to which the thermistor chain can reach when being towed at 10 knots. These DSL waves show a correlation with the isothermal waves recorded by the thermistor chain and suggest that the whole layer between 20 m and 250 m participates simultaneously in these oscillations.

Figure 16 is an example of such a correlation, but it should be noted that such DSL records can only be obtained in favourable conditions of light when the DSL is at its maximum depth. This figure also shows the vertical migration of the DSL towards the surface at sunset starting at 1835.

An especially interesting record of this type (Fig. 17) was obtained while steaming westwards through a train of waves from a point 19 miles east of Gibraltar. Oscillations were recorded at each of the three deepest layers - 120, 100, and 60 fathoms - and ten distinct waves are observable. After the passage of the trailing wave at 2045, both the isotherms and the DSL resumed a uniform distribution and profile.

## 11. ANALYSIS OF WAVE TRAINS

Another phenomenon has been observed, occurring at the front of wave trains. As is shown on the top chart in Fig. 18, the surface temperature is observed to drop by as much as $4^{o}C$ as the ship approaches and passes over the wave front. On the occasion when this record was made, the ship was travelling westwards along the axis of the Strait. At point A (map in Fig. 18), 12 miles southeast of the Rock, it met the front of a wave train about to dissipate itself into the Mediterranean;passing through this train,it then, on reaching point B, met the front of another train just being formed over the Sill. Judging by this type of record, it would seem feasible to use air radiation thermometers to record, with rapid sweeps, the positions of the wave fronts as a function of time. Caution should be taken in interpreting such data, because one must take into account that at certain phases of the tide there is an upwelling of deep water in the Tarifa Region (see Fig. 6) due to other dynamic processes.

The record of this particular run also provides interesting evidence of the heights of the waves at the Sill and east of the Rock. The second diagram in

Fig. 18, which is the record of the thermistor chain (T. C. R.), shows that the dip in the $14^{o}C$ caused by the wave forming over the Sill at H. W. -2 was of the order of 105 m, whereas that caused by the wave passing into the Mediterranean at H. W.- 5 1/2 was only about 45 m.

The third diagram on Fig. 18 shows the shear velocity relative to the surface current measured by a pitot tube installed on the chain next to the lowest thermistor link. The chart expresses these values as positive or negative deviations from a zero speed value (in knots). It is quite clear that large changes in shear velocity are associated with large amplitudes in the isotherm oscillations. This suggests changes in particle velocity and favours the theory of internal waves.

Part of the 1961 programme was to run at 10 knots back and forth longitudinally through a single wave train to study its characteristics during its progression towards the Mediterranean. Figure 19 (a and b) shows the results of this study. The four circles on the map show the progressive positions of the front of the wave trains while the four profiles were recorded.

The distances between these positions provide an indication of the average velocity of this wave train which appeared to increase from the Sill eastward. It appears to be about 1. 3, 4, and 4. 4 knots respectively from positions 1 to 2, 2 to 3, and 3 to 4.

Unfortunately, it was not possible to make simultaneous current measurements, so it is not possible to establish whether the waves were moving at the same speed as the water layers or if they were moving independently at their own speed.

Another method to establish this fact could have been by obtaining evidence of a Doppler effect when the ship was navigating in two directions relative to the waves.

From the profiles shown in Fig. 19 it is difficult to recognise the Doppler effect. Profiles 1 and 3 (solid lines) were obtained when the ship was travelling at constant rpm against the waves and profiles 2 and 4 (dashed lines) when it was travelling at constant rpm with the waves. Whereas in Fig. 19b the frequency of profile 3 is nearly double that of profile 4, in Fig. 19a profile 2 precedes profile 1 instead of lagging behind it. There is therefore insufficient evidence on which to draw conclusions.

The temperature profile of this wave train (represented here only by the 15°C isotherm, for the sake of simplicity) did not change very much between position 1 and 2 but changed considerably between position 2 and 3 and between position 3 and 4. By the last position, the waves assumed a more definite charater: their wave length increased, and their amplitude decreased slightly.

The arrival of the front of waves along the axis of the Strait occurred that day at - 1.50, - 0.05, + 0.55 and + 4.27 hours and minutes from high-water in Gibraltar, showing that this disturbance is not in phase with the tide. However, as shown previously on page 18, the front arrivals vary from day to day, at the same position, within a certain time interval. It is felt that this could be accurately established by statistical methods.

## 12. CONCLUSIONS

It has become apparent that the results of both classical oceanographic measurements and the more sophisticated measurements reviewed in this paper can be summarised in simplified models that may lead to a better understanding

of the general mechanism of the events occurring in the Strait. For prediction of these events, however, further measurements are still required.

The present model, shown in Fig. 20, concerns only the centre channel of the area east of the Sill, leaving the area west of the Sill for future studies. This centre channel is that outlined by the 100 fathom contours, excluding the waters around the Rock of Gibraltar; in shallower water and near the Rock the vertical gradients of temperature and salinity are shallower and the model does not apply.

In the model, the interfaces (double lines on the left-hand diagram) are shown at their extreme depth and the current velocities (long arrows on the right-hand diagram) at their maximum value; however, values of down to zero have been recorded for all these parameters on different occasions.

As the model shows, in the centre channel area one can consider the existence of a three-layered body of water:

<u>The Bottom Layer</u> is composed of practically homogeneous Mediterranean water, with a salinity of 38‰ $\pm$ 0.2‰* and a temperature of 13°C $\pm$ 0.2°C, which moves westwards at speeds of less than 1 knot.

<u>The Intermediate Layer</u> is characterised by a high salinity gradient of from 38‰ to 36‰ and a shallow temperature gradient of from 13°C to 15.5°C; it flows east or west, according to the tides, at speeds not exceeding 1 1/2 knots.

---

*As mentioned before, this value may eventually be set a little higher.

This layer is about 160 m thick near the Sill and about 120 m thick in the Gibraltar Region (GB on Fig. 21). The depth of its interface with the Bottom Layer can be found at anything from 300 m to 140 m. Oscillations of this lower interface have been recorded by recording the vertical displacements of the Deep Scattering Layer in favourable conditions of light.

<u>The Surface Layer</u> is characterised by a generally shallow salinity gradient of 36‰ to 36.3‰ throughout the year and a variable temperature gradient, which, in the summer, is from 15.5$^{o}$C to 22$^{o}$C. This water flows mostly eastwards at speeds that reach a maximum, under favourable wind conditions, of 6 knots. With contrary winds, only the first 10 to 15 m are slowed down. Speeds of up to 5 knots have been recorded at depths of 50 m, while the first 10 m of surface water was flowing at 4 knots or less in the same direction. (Extreme current velocities are indicated on the right-hand side of the figure.) The interface between the surface and intermediate layers has been recorded, through the various years of observation, at any depth from the surface to about 140 m at the Sill and to about 100 m in the Gibraltar region. It oscillates with tidal and shorter periods, as is revealed by continuous temperature measurements made with the thermistor chain.

This eastern area of the Strait is clearly the simplest area to understand, but in order to appreciate the interplay of the several dynamic factors it will be necessary to make simultaneous long-term observations of temperature and current distributions by means of accurate instruments suspended from low-drag oceanographic buoys anchored in the Gibraltar Region of the Strait. With such data covering a period of 20 to 30 days in each season of the year, it is hoped to formulate a prediction method. This is the purpose of future expeditions to the Strait, the first of which will be made during October 1964.

In the second model (Fig. 2[illegible]) a tentative explanation is given of the most evident facts recorded about the trains of internal waves. The 14$^{o}$C isotherm

is taken as a representative profile. The hydraulic head of the eastward moving Atlantic water exercises a pressure on the breaking mass of the Mediterranean water, which is then forced eastwards and consequently rises to the surface, constricting and thus increasing the velocity of the eastward-flowing surface water. A cold patch of upwelling water from the intermediate layer can then be observed on the surface. The great vertical displacements along the sloping front cause very distinct surface ripples to form over the crests of the first three or four waves. Measurements of the deep currents suggest that there is an orbital motion of the water particles, a fact which could favour theories of internal waves.

## 13. RECOMMENDATIONS AND FUTURE WORK

Important features of the complex dynamics of the Strait have been revealed by the measurements described in this report. So far, however, measurements have been taken mainly from April to October and from a ship that was always moving, even when it was attempting to hold a stationary position against the strong, variable winds and currents.

One of the most important things that must now be established is the correlation between the current velocities and the directions of both the surface layers and the internal waves. The next thing will then be to record the vertical displacements and the depths of the layer interfaces over a large area in order to make a mathematical model of these features as functions of time and space. This will later permit prediction methods to be formulated.

The necessary data would best be provided from a few fixed positions at representative locations across the Strait and along its axis. At each position a vertical array of instruments reaching from near the surface to the bottom should take continuous measurements for periods of from 20 to 30 days in each of the four seasons. To satisfy these requirements a low-drag,

miniature, sub-surface, self-recording oceanographic buoy has been designed and constructed in this laboratory and will be used in the Strait for the first time during October 1964.

In addition to the measurements made by the buoys, it would also be advantageous to use a fast aircraft to record surface temperatures with an air radiation thermometer, to photograph surface ripples, and possibly to follow the behaviour of surface dyes released from a ship, thereby providing a synoptic coverage of the entire surface of the Strait. Deep scattering layer recordings should also be made at the same time, and simultaneous meteorological, sea level, and tidal data should be collected.

For a more precise interpretation of the results of these measurements, a detailed topographic survey by means of narrow-beam transducers and precise electronic navigation systems is planned for the coming years. Linked with this work will be a study of the bottom characteristics in special areas by means of a "Troika" deep sledge carrying cameras and slope-measuring inclinometers, and by means of bottom corers. Bottom current measurements will also be made by means of self-recording instruments being developed at this laboratory.

## REFERENCES


1. G. Giermann, "Erläuterungen zur Bathymetrischen Karte der Strasse von Gibraltar," Bull. Inst. Ocean., Monaco, No. 1218A, 30 Oct. 1961.

2. H. Lacombe and P. Tchernia, "Quelques Traits Généraux de l'Hydrologie Méditerranéenne d'après diverses campagnes hydrologiques récentes en Méditerranée, dans le proche Atlantique et dans le Détroit de Gibraltar," Extrait des Cahiers Océanographiques, XXII$^{e}$ année, No. 8, sept-oct 1960.

3. G. Wüst, "Die Tiefenzirkulation des Mittelländischen Meeres in den Kernschichten des Zwischen - und des Tiefenwassers," Deutsche Hydrographische Zeitschrift, No. 13, 1960, pp. 105-131.

4. H. Sverdrup, "The Oceans, their Physics, Chemistry, and General Biology," Prentice (c1942).

5. J.P. Jacobsen and H. Thomsen, "Periodical Variations in Temperature and Salinity in the Strait of Gibraltar," James Johnstone Memorial, Vol. 275-293, 1934, Liverpool University Press.

6. R. Frassetto, R.H. Backus, and E. Hays, "Sound Scattering Layers and their Relation to Thermal Structure in the Strait of Gibraltar," Deep Sea Research, Vol. 8, Nol. 1, 1961, pp. 69-72.

7. H. Lacombe, P. Tchernia, C. Richez, and L. Gamberoni, "Deuxième Contribution à l'Etude du Régime du Détroit de Gibraltar," (Travaux de 1960), Cahiers Oceanographiques, XVI$^{e}$ année, No. 4, avril 1964.

8. R. Frassetto, "A Preliminary Survey of Thermal Microstructure in the Strait of Gibraltar," Deep Sea Research, Vol. 7, No. 3, 1960, pp. 152-162.

9. G. Peluchon, "Travaux Océanographiques de l'"ORIGNY" à Gibraltar," Résultats des observations océanographiques effectuées en mai et juin 1961 dans la région du détroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. I - oct. 1962, pp. 323-325.

10. E.C. La Fond, "Slicks and Temperature Structure in the Sea," U.S.N. Electronic Lab., Rpt 937.

## FURTHER BIBLIOGRAPHY

M. Bockel, "Hydrologie dans le détroit," Résultats des observations océanographiques effectuées en mai et juin 1961 dans la région du détroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. I - oct. 1962, pp. 325-329.

G. Boyum, "Hydrology and Currents in the Area West of Gibraltar," Results from the "Helland-Hansen" Expedition May-June 1961. Résultats des observations océanographiques effectuées en mai et juin 1961 dans la région détroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. IV, mai 1963.

J.R. Donguy, "Courants de surface dans le détroit de Gibraltar," Cahiers Océanographiques, XIV$^{e}$ année, no. 7, juillet-aout 1962, pp. 474-483.

J.R. Donguy, "Courants de surface dans le détroit de Gibraltar," Résultats des observations océanographiques effectuées en mai et juin 1961 dans la région du détroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. I - oct. 1962, pp. 474-483.

J.R. Donguy, "Hydrologie en Mer d'Alberan," Résultats des observations océanographiques effectuées en mai et juin 1961 dans la région du détroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. I - oct. 1962, pp. 573-578.

J.R. Donguy, "Etude du Régime des courants superficiels dans le Détroit de Gibraltar en relation avec la température de surface," Résultats des observations océanographiques effectuées en mai et juin 1961 dans la région du détroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. V - fév. 1964, pp. 626-721.

R. Frassetto, "Unpublished Data of Surveys made in the Strait of Gibraltar in 1958, 1959 and 1961 in conjunction with the Woods Hole Oceanographic Institution."

R. Grousson and J. Faroux, "Mesure de courants de surface en Mer d'Alboran," Résultats des observations océanographiques effectuées en mai et juin 1961 dans la région du détroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. V - fév. 1964, pp. 716-721.

H. Lacombe, "Contribution à l'etude du régime du détroit de Gibraltar" (Travaux de 1957-1958), I - Etude dynamique - Extrait des Cahiers Océanographiques, XIII^e année, No. 2, fév. 1961.

H. Lacombe and C. Richez, "Contribution à l'etude du régime du détroit de Gibraltar," (Travaux de 1957-1958), II - Etude Hydrologique, Extrait des Cahiers Océanographiques, XIII^e année, No. 5, mai 1961.

H. Lacombe and R. Bonnefille, "Note préliminaire sur la réalisation d'un modèle réduit tournant du détroit de Gibraltar," E.D.F. Centre de Recherches et d'Essais de Chatou, Departement Laboratoire National d'Hydraulique.

H. Lacombe, " Mesure du courant, d'Hydrologie et de Météorologie effectuées à bord de la "CALYPSO." Résultats des observations océanographiques effectuées en mai et juin 1961 dans la région du détroit de Gibraltar. Project Gibraltar. S.C.O.O.T.A.N. Fasc. V - fév. 1964, pp. 23-94.

E.C. La Fond, "Sea Surface Features and Internal Waves in the Sea," Indian Journ. Meteo. & Geoph., Vol. 10, No. 4, pp. 415-419.

H. Mosby, "Current Measurements, Meteorological Observations and Soundings of the M/S "HELLAND-HANSEN" near the Strait of Gibraltar," Rêsultats des observations ocêanographiques effectuêes en mai et juin 1961 dans la rêgion du dêtroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. III - aout 1962.

H. Mosby, "Hydrological observations of the M/S "HELLAND-HANSEN," Rêsultats des observations ocêanographiques effectuêes en mai et juin 1961 dans la rêgion du dêtroit de Gibraltar. Project Gibraltar, S.C.O.O.T.A.N. Fasc. II - aout 1962.

# DISTRIBUTION LIST

| | |
|---|---|
| Minister of Defense<br>Brussels, Belgium | 10 copies |
| Minister of National Defense<br>Department of National Defense<br>Ottawa, Canada | 10 copies |
| Chief of Defense, Denmark<br>Kastellet<br>Copenhagen Ø, Denmark | 10 copies |
| Minister of National Defense<br>Division Transmissione-Ecoute-Radar<br>51 Latour Maubourg<br>Paris 7e, France | 10 copies |
| Minister of Defense<br>Federal Republic of Germany<br>Bonn, Germany | 10 copies |
| Minister of Defense<br>Athens, Greece | 10 copies |
| Ministry of National Defense<br>Navy General Staff<br>Rome, Italy | 10 copies |
| Minister of National Defense<br>Plein 4, The Hague,<br>Netherlands | 10 copies |
| Minister of National Defense<br>Storgaten 33,<br>Oslo, Norway | 10 copies |
| Minister of National Defense, Portugal<br>Care Portuguese Military Attaché<br>3 Rue Noisiel<br>Paris, France | 10 copies |
| Minister of National Defense<br>Ankara, Turkey | 10 copies |
| Minister of Defense<br>London, England | 18 copies |
| Supreme Allied Commander Atlantic<br>(SACLANT)<br>Norfolk 11, Virginia | 5 copies |
| SACLANT Representative in Europe<br>(SACLANTREPEUR)<br>Place du Marechal de Lattre de Tassigny<br>Paris 16e, France | 1 copy |
| Commander in Chief<br>Western Atlantic Area<br>(CINCWESTLANT)<br>Norfolk 11, Virginia | 1 copy |
| Commander in Chief<br>Eastern Atlantic Area<br>(CINCEASTLANT)<br>Eastbury Park, Northwood<br>Middlesex, England | 1 copy |
| Maritime Air Commander<br>Eastern Atlantic Area<br>(COMAIREASTLANT)<br>R.A.F. Northwood<br>Middlesex, England | 1 copy |
| Commander Submarine Force<br>Eastern Atlantic<br>(COMSUBEASTLANT)<br>Fort Blockhouse<br>Gosport, Hants, England | 1 copy |
| Commander, Canadian Atlantic<br>(COMCANLANT)<br>H.M.C. Dockyard<br>Halifax, Nova Scotia | 1 copy |
| Commander Ocean Sub-Area<br>(COMOCEANLANT)<br>Norfolk 11, Virginia | 1 copy |
| Supreme Allied Commander Europe<br>(SACEUR)<br>Paris, France | 7 copies |
| SHAPE Air Defence Technical Center<br>P.O. Box 174<br>Stadhouders Plantsoen 15<br>The Hague, Netherlands | 1 copy |
| Allied Commander in Chief Channel<br>(CINCCHAN)<br>Fort Southwick, Fareham<br>Hampshire, England | 1 copy |
| Commander Allied Maritime Air Force Channel<br>(COMAIRCHAN)<br>Northwood, England | 1 copy |
| Commander in Chief Allied Forces Mediterranean<br>(CINCAFMED)<br>Malta, G.C. | 1 copy |
| Commander South East Mediterranean<br>(COMEDSOUEAST)<br>Malta, G.C. | 1 copy |

Commander Central Mediterranean
(COMEDCENT)
Naples, Italy — 1 copy

Commander Submarine Mediterranean
(COMSUBMED)
Malta, G.C. — 1 copy

Standing Group, NATO
(SGN)
Room 2C256, The Pentagon
Washington 25, D.C. — 3 copies

Standing Group Representative
(SGREP)
Place du Marechal de Lattre de Tassigny
Paris $16^e$, France — 5 copies

National Liaison Representatives

NLR Belgium
Belgian Military Mission
3330 Garfield Street, N.W.
Washington, D.C. — 1 copy

NLR Canada
Canadian Joint Staff
2450 Massachusetts Avenue, N.W.
Washington, D.C. — 1 copy

NLR Denmark
Danish Military Mission
3200 Whitehaven Street, N.W.
Washington, D.C. — 1 copy

NLR France
French Military Mission
1759 "R" Street, N.W.
Washington, D.C. — 1 copy

NLR Germany
German Military Mission
3215 Cathedral Avenue, N.W.
Washington, D.C. — 1 copy

NLR Greece
Greek Military Mission
2228 Massachusetts Avenue, N.W.
Washington, D.C. — 1 copy

NLR Italy
Italian Military Mission
3221 Garfield Street, N.W.
Washington, D.C. — 1 copy

NLR Netherlands
Netherlands Joint Staff Mission
1470 Euclid Street, N.W.
Washington, D.C. — 1 copy

NLR Norway
Norwegian Military Mission
2720 34th Street, N.W.
Washington, D.C. — 1 copy

NLR Portugal
Portuguese Military Mission
2310 Tracy Place, N.W.
Washington, D.C. — 1 copy

NLR Turkey
Turkish Joint Staff Mission
2125 LeRoy Place, N.W.
Washington, D.C. — 1 copy

NLR United Kingdom
British Defence Staffs, Washington
3100 Massachusetts Avenue, N.W.
Washington, D.C. — 1 copy

NLR United States
SACLANT
Norfolk 11, Virginia — 40 copies

Scientific Committee of National Representatives

Dr. J.E. Keyston
Defense Research Board
Department of National Defense
Ottawa, Canada — 1 copy

G. Meunier
Ingenieur en Chef des Genie Maritime
Services Technique des Constructions et
Armes Navales
8 Boulevard Victor
Paris $15^e$, France — 1 copy

Dr. E. Schulze
Bundesministerium der Verteidigung
ABT H ROMAN 2/3
Bonn, Germany — 1 copy

Commander A. Pettas
Ministry of National Defense
Athens, Greece — 1 copy

Professor Dr. Maurizio Federici
c/o MARICOMITARMI
Ministero della Marina
Rome, Italy — 1 copy

Dr. M.W. Van Batenburg
Physisch Laboratorium RVO-TNO
Waalsdorpvlakte
The Hague, Netherlands — 1 copy

Mr. A.W. Ross
Department of Physical Research
Admiralty, Whitehall
London S.W. 1, England — 1 copy

Dr. J.E. Henderson
Department of Physics
University of Washington
Seattle 5, Washington — 1 copy

| | |
|---|---|
| CC R. C. Lambert<br>Etat Major Général Force Navale<br>Caserne Prince Baudouin<br>Place Dailly<br>Bruxelles, Belgique | 1 copy |
| CAPT H. L. Prause<br>Søvaernets Televaesen<br>Lergravsvej 55<br>Copenhagen S', Denmark | 1 copy |
| Mr. F. Lied<br>Norwegian Defense Research<br>Establishment<br>Kjeller, Norway | 1 copy |
| Ing. CAPT N. Berkay<br>Seyir Ve HDR D<br>CUBUKLU<br>Istanbul, Turkey | 1 copy |
| Dr. P. M. Fye<br>Woods Hole Oceanographic<br>Institution<br>Woods Hole, Mass. | 1 copy |
| Mr. Sv. F. Larsen<br>Danish Defense Research Board<br>Østerbrogades Kaserne<br>Copenhagen Ø, Denmark | 1 copy |
| CDR R. J. M. Sabatier<br>EMM/TER<br>2 Rue Royale<br>Paris 8e, France | 1 copy |
| CF V. Gioncada<br>Stato Maggiore della Marina<br>Roma, Italy | 1 copy |
| CDR F. J. Kelley<br>Box 39, Navy No. 100<br>U.S. Navy | 1 copy |
| ASG for Scientific Affairs<br>NATO<br>Porte Dauphine<br>Paris 16e, France | 1 copy |